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Potential for measuring production forgone as a metric for assessing project impacts to habitat on fisheries productivity

R.G. Randall, M.J. Bradford[1], M.A., Koops, and A. van der Lee

Fisheries and Oceans Canada
Great Lakes Laboratory for Fisheries and Aquatic Sciences
Burlington, ON L7S 1A1

[1]Fisheries and Oceans Canada
School of Resource and Environmental Management
Simon Fraser University
Burnaby BC, V5A 1S6

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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TABLE OF CONTENTS

ABSTRACT IV
RÉSUMÉ IV
INTRODUCTION 1
METHODS 1
ATLANTIC SALMON 2
YELLOW PERCH 4
GENERIC PRODUCTION FORGONE ANALYSIS 4
RESULTS 6
ATLANTIC SALMON 6
YELLOW PERCH 8
GENERIC PRODUCTION 9
DISCUSSION 11
ACKNOWLEDGEMENTS 13
REFERENCES 13

ABSTRACT

Production forgone is defined as the fish biomass that would have resulted from the survival and growth of the fish lost to a project because of changes to habitat quantity or quality. Production forgone is advantageous as a productivity metric because it accounts for the energy (biomass) that could potentially be transferred to other trophic levels or be available for harvest. In this pilot study, it was shown to be feasible to estimate production forgone for two species where detailed data on age-specific densities, growth and survival were known. Production forgone was estimated for the area-per-recruit of each species, to provide a metric of productivity that complements adult equivalents as a common currency for estimating fish productivity. Because of the extensive data requirements, production forgone would most likely be a useful metric if a detailed assessment was needed to determine offsets for a large project.

Potentiel de mesure du manque à produire comme paramètre aux fins de l'évaluation des impacts des projets dans l'habitat sur la productivité des pêches

RÉSUMÉ

Le manque à produire se définit comme étant la biomasse de poisson qui serait issue de la survie et de la croissance du poisson perdu à la suite d'un projet ayant entrainé des changements de la quantité ou de la qualité de l'habitat. Il est avantageux de connaître le manque à produire sous forme de paramètre de la productivité, car il correspond à l'énergie (biomasse) qui aurait pu être transférée à d'autres niveaux trophiques ou être disponible pour la pêche. Dans le cadre de cette étude pilote, il s'est avéré possible d'estimer le manque à produire de deux espèces dont la densité selon l'âge, la croissance et la survie étaient connues. Le manque à produire a été estimé pour le recrutement par zone de chaque espèce afin d'obtenir un paramètre de la productivité qui complète les équivalents-adultes en tant qu'unité commune pour estimer la productivité du poisson. En raison des vastes exigences en matière de données, le manque à produire serait fort probablement un paramètre utile si une évaluation détaillée était nécessaire pour déterminer les mesures de compensation d'un grand projet.

INTRODUCTION

Amendments were made to Canada's *Fisheries Act* in 2012. The new Fisheries Protection Provisions apply to land-based or in-water development activities that have the potential to adversely affect fish or fish habitat, resulting in a loss of fisheries productivity. Decision making by Fisheries and Oceans Canada (DFO), Fisheries Protection Program (FPP) is guided by the purpose statement (s 6.1) of the act: to 'provide for the sustainability and ongoing productivity of commercial, recreational and Aboriginal (CRA) fisheries'. Science advice on the interpretation and potential metrics for measuring ongoing productivity has been provided (DFO 2013; DFO 2014 a, b, c, d; DFO 2015). Based on this advice and other factors, the FPP is developing a project review and decision making process that will provide a consistent, transparent and efficient framework for the application of the new Provisions.

Development activities can have a wide range of impacts to metrics of fish productivity, ranging from direct mortality, changes to life history processes (growth or reproduction) and to changes in the quantity and quality of fish habitat. Having a common currency of one metric of fish productivity can assist in the development of regulatory thresholds that are consistent across the diversity of activities and the regions of Canada. Converting ecosystem damages to the loss of Equivalent Adults has been proposed as one such measure (DFO 2015).

Consistent with equivalent adults, the measurement of fish production of all life stages leading to adult recruitment would provide an ecologically sound and complementary measure to the numbers of adults lost. Rago (1984) introduced the concept of production forgone as a method for assessing the consequences to fish populations of powerplants that cause mortality through entrainment. Production forgone was defined as the biomass that would have been elaborated by the fish lost to entrainment or impingement mortality. Rago argued that production was more relevant for ecosystem assessment than numbers lost because production (of biomass) included the energy that could potentially be transferred to other trophic levels through consumption or decomposition. The production forgone approach recognizes that losses to ecosystem productivity are both immediate and propagated through time. Since its inception, production forgone has been proposed as a general method for measuring the significance of stressors on fish populations (Boreman 2007; Power 2007).

Changes to habitat quantity or quality that negatively affect productivity will result in losses of fish production in the short and long term. The objective of this study was to determine the feasibility of using production or production forgone as a metric for measuring impacts to changes in habitat quantity and/or quality. Production forgone as a direct metric of productivity, in the context of this paper, is proposed as a complementary metric to equivalent adults. That is, the habitat area needed to produce one adult fish provides a spatial context for comparing equivalent adults with fish biomass and production as complementary metrics of habitat value.

METHODS

To demonstrate the utility of the production forgone approach, fish production was estimated using detailed population data for two case study species, Atlantic Salmon (*Salmo salar*) and Yellow Perch (*Perca flavescens*) and, additionally, using a generic body size approach for four size classes of freshwater fishes. The case study species and the generic approach were also used in the detailed analysis of equivalent adults (DFO 2015).

ATLANTIC SALMON

Empirical field data on juvenile Atlantic Salmon parr densities, weights, biomass and survival were obtained from Douglas et al. (2013) (Figure 1). These survey data are collected as part of a larger data set that was used to assess the status of Atlantic Salmon for fisheries management. Juvenile salmon data were obtained from the Southwest Miramichi River, New Brunswick, using a standardized electrofishing protocol from 1970 to 2014. For this study, average density for the period 1985–2011 was used after significant management changes in 1984 (Douglas et al. 2013; Figure 23). The number of sites each year ranged from 22 to 30. The electrofishing survey methods and analysis of temporal trends of the juvenile salmon are described in detail by Chaput et al. (2010).

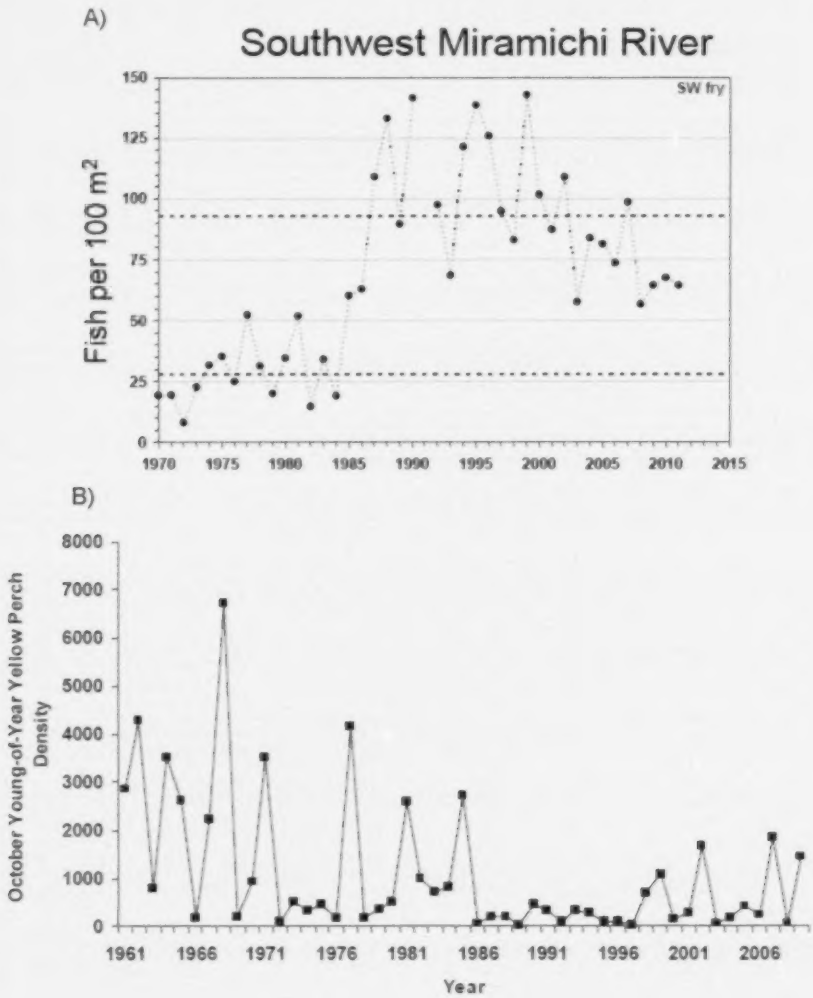

Figure 1. Long term trends in the abundance of juvenile Atlantic Salmon (age 0) in the SW Miramichi River, NB (reproduced from Douglas et al. 2013) and yellow perch (age 0) in Lake Oneida, NY (reproduced from Jackson et al. 2010).

Equivalent adults (EA) and area-per-recruit (APR) for Atlantic Salmon were calculated using equations from M. Bradford, as briefly summarized here. Input data included the densities of age 0 fry, ages 1 and 2 parr and age 3 smolts. Area per individual (API) was calculated as the inverse of density for each age group. Annual survival (S) among the juvenile salmon ages in freshwater was calculated from the ratio of densities. Survival of smolts to adult was also available (Douglas et al. 2013), which was also used to estimate survival to adult and EA numbers for each age group. Area per recruit (APR) was the product of EA and API. Input data and calculation details for Atlantic Salmon are given in Table 1.

Table1. Density (m^{-2}), size (length, cm; weight, g), biomass, survival (annual) and area per recruit (m^2) estimates for Atlantic Salmon and Yellow Perch.

Atlantic Salmon

Age (years)	Density (m^{-2})	Length (cm)	Weight (g)	Biomass (g m^{-2})	API (m^2)	S	Survival to adult	EA	APR
0	*0.900*	*5.4*	1.6	1.45	1.11		0.002	660	734
1	*0.220*	*8.9*	7.0	1.54	4.55	0.24	0.006	161	734
2	*0.040*	*11.8*	16.2	0.65	25.00	0.18	0.034	29	734
3	*0.029*				34.48	0.73	*0.047*	21	734

Yellow Perch

Age (years)	Density (m^{-2})	Length (cm)	Weight (g)	Biomass (g m^{-2})	API (m^2)	S	Survival to adult	EA	APR
0	0.0780	69.1	3.2	0.25	12.8		0.018	56	
1	0.0043	120.7	18.5	0.08	235.3		0.39	3	
3	0.0016	225.9	135.5	0.22	615.4				719

Input values are in italics, others are derived
Atlantic salmon: Data are for Southwest Miramichi (SW)
Density: Age 0 to age 3 are from Douglas et al. 2013 (Figure 23 and Table 12)
Length: average for SW 2001–2006 from S. Douglas (pers. comm.)
*Weight: 0.01*length^3*
Area per individual (API): inverse of density
Annual survival S: the ratio of density between ages (e.g., density age 1/density age 0)
*Survival to adults: [S (age_{i+1}) *survival to adult (age_{i+1})], with survival to adults of smolt (0.047) as starting point*
Equivalent Adult (EA): inverse of survival to adults
*Area per recruit (APR): EA*API*
Yellow perch: Data from Jackson et al. 2010, as compiled and calculated (S, API, EA and APR) by M. Bradford

Following Rago (1984), growth, mortality, average biomass and production rate were estimated by the instantaneous growth rate method (also see Ricker 1975):

$$G_t = \ln\left(\frac{W_{t+1}}{W_t}\right) \text{ (instantaneous growth rate during t)} \quad (1)$$

$$M_t = -ln\left(\frac{N_{t+1}}{N_t}\right) \text{ (instantaneous mortality rate during t)} \quad (2)$$

$$\bar{B}_t = \sum_{i=t}^{T_{max}} \frac{B_i\left(e^{G_i - M_i} - 1\right)}{G_i - M_i} \text{ (average biomass during t; g)} \quad (3)$$

$$P_t = G\bar{B} \quad \left(= \sum_{i=t}^{T_{max}} \frac{G_i B_i\left(e^{G_i - M_i} - 1\right)}{G_i - M_i}\right) \text{ (production rate, g } m^{-2}\ y^{-1}) \quad (4)$$

$$B_m = \bar{B}_t(1\text{-}e^{-M})\ (biomass\ loss\ to\ natural\ mortality) \quad (5)$$

Anadromous juvenile Atlantic Salmon in the Miramichi River, New Brunswick, emerge from the gravel in mid-June at a size of about 0.2 g (Randall 1982) and rear in freshwater for 2 to 3 years before emigrating from the river as smolts. Using the average body size and density data for each age-group, annual freshwater production was estimated for four time periods – emergence to mid-summer fry, fry to age 1 parr, age 1 parr to age 2 parr, and parr to smolts. On average, for each section of fluvial habitat, three age-groups were contributing to juvenile production during the growing season. Total freshwater production was estimated per unit area (m^2) and for the area needed (APR) for an EA. Estimating production for the APR provided a convenient way to directly compare APR and production as currencies for measuring habitat value in the context of fisheries productivity.

YELLOW PERCH

Yellow Perch abundance and other co-habiting species in Lake Oneida, New York, have been monitored for many years by biologists with the Cornell Field Station to maintain a long-term database (1961 to 2009; Jackson et al. 2010) (Figure 1). Oneida Lake supports a significant recreational fishery, of which Yellow Perch catch is an important component. Adult Yellow Perch numbers were estimated from catch in standard gill net sets, adjusted for estimates of fish catch efficiency. Abundance of Yellow Perch at the larval stage was estimated using bottom trawls in the fall (October).

Average density, mean size and survival of age 0, age 1 and age 3 perch were estimated from 1962 to 1976, as compiled by M. Bradford (Table 1). Weight-at-age was estimated using a length-weight relationship with coefficients specific for this population. Growth, average biomass and production were estimated for annual periods using the equations given above.

EA and APR for yellow perch were calculated using the same algorithms used for Atlantic Salmon (Table 1).

GENERIC PRODUCTION FORGONE ANALYSIS

It may be necessary to estimate the impact of a project when data are limited or nonexistent. In this scenario, a range of estimates of production forgone can be estimated using a generic simulation based approach. The generic approach we employ utilizes a simple life history model to estimate growth and mortality from known life history constants and allometric relationships.

For simplicity, production forgone estimates are produced for four size classes of fish based on estimates of adult length (the geometric mean of species length-at-maturity, L_{mat}, and maximum length, L_{max}) of Canadian species (n = 178; Coker et al. 2001). The size classes are defined as: 1. <20 cm (n = 95); 2. 20 to 40 cm (n = 41); 3. 40 to 70 cm (n = 28); and 4. >70 cm (n = 14). The life history constants (longevity, T_{max}; age-at-maturity, T_{mat}; maximum length, L_{max}; and length-at-maturity, L_{mat}) required in the generic life history model were taken from a compilation of life history characteristics of Canadian freshwater species (Coker et al. 2001). The median value across species within each size class was computed for each variable and then used to estimate growth and mortality.

Growth is assumed to follow a simple von Bertalanffy growth function (VBGF) where length, L, at age, t, is:

$$L_t = L_\infty\left(1 - e^{-kt}\right) \quad (6)$$

L_∞ is the asymptotic length which can be estimated from L_{max} (Froese and Binohlan 2000) as:

$$log_{10}(L_\infty) = 0.044 + 0.9841 \times log_{10}(L_{max}) \quad (7)$$

The von Bertalanffy growth coefficient, k, is related to L_∞ (Beverton and Holt 1959). Using data from FishBase (Froese and Pauly 2005) this relationship can be expressed as:

$$log_{10}(k) = 0.419 - 0.6105 \times log_{10}(L_\infty) \quad (8)$$

Weights (g) are estimated from lengths assuming isometric growth ($W_t = 0.01 \times {L_t}^3$) from which instantaneous growth, G, is estimated.

Mortality is inherently difficult to estimate accurately (Kenchington 2014). As a result, to provide a range of potential estimates we employ three different mortality relationships. The first relationship used to estimate instantaneous mortality, M, uses the form proposed by Jensen (1996)

$$M = 1.5k \quad (9)$$

Our second estimate of M is based on a regression with maximum age, T_{max} (Hoenig 1983):

$$M = 4.31{T_{max}}^{-1.01} \quad (10)$$

Finally, we use an allometric relationship predicted from weight (Lorenzen 1996)

$$M_t = 3{W_t}^{-0.288} \quad (11)$$

This type of relationship is useful for estimating a generic size-based relationship but it may be difficult to capture species-specific differences.

Equation 11 can estimate mortality for different ages which can be converted to survival; however, Equations 9 and 10 produce only single estimates of adult mortality. Lorenzen (2000) found that mortality was inversely proportional to body length and is best explained by:

$$M = \frac{m_0}{L} \quad (12)$$

m_0 represents instantaneous mortality at one unit length (i.e., $L = 1$ *cm*). Assuming equations 9 and 10 produce estimates of M at L_{max}, $m_0 = ML_{max}$

The survival rate of each age class, S_t, can be calculated by integrating equation 12 and evaluating between t and $t+1$:

$$S_t = \left[\frac{L_t e^{-k}}{L_{t+1}}\right]^{\frac{m_0}{kL_\infty}} \quad . (13)$$

S_t can be converted into age-specific estimates of M.

Production forgone is estimated for a loss equivalent to one recruit (at age-of-maturity). This requires an estimate of the number of individuals of each age class equivalent to a fish at T_{mat}:

$$N_t = \begin{cases} \prod_{i=t}^{T_{mat-1}} 1/S_i & If\ t < T_{mat} \\ 1 & If\ t = T_{mat} \\ \prod_{i=T_{mat+1}}^{t} S_i & If\ t > T_{mat} \end{cases} \quad (14)$$

The loss of one recruit can be expressed as a loss of habitat by estimation the area-per-recruit (APR):

$$APR_t = API_t \times N_t, \quad (15)$$

where API_t is the age class specific area-per-individual or the area occupied by a single individual of age class t. This is related to length and based on empirical data of age-specific densities (Bradford unpubl. data) and can be predicted for lakes and rivers respectively from:

$$API_t = e^{-7.215} \times L_t^{2.519}, \quad (16)$$

$$API_t = e^{-10.7787} \times L_t^{2.884} \quad (17)$$

RESULTS

ATLANTIC SALMON

Juvenile salmon densities averaged 0.90, 0.22, and 0.04 m^{-2} for age 0, 1 and 2 salmon, respectively (Table 1). Total standing biomass of juvenile salmon averaged 3.6 g m^{-2}. The number of out-migrating smolts in the Southwest Miramichi averaged 0.029 m^{-2} (Douglas et al. 2013). The average survival from smolts to adults was 0.047. This survival resulted in an area/adult (APR) estimate of 734 m^2 (Table 1).

Production rate varied but generally decreased with age, from 2.19 (for fry-age 1) to 0.3 g m^{-2} y^{-1} (for large parr to smolts) (Table 2) (Figure 2). Production immediately following emergence was calculated for a short period only, but was considerable (1.41 g m^{-2} for the period of fry emergence to midsummer). Total juvenile production was 4.76 g m^{-2} y^{-1}. As expected by calculation, growth, P/B and production were strongly related to body size (Figure 3). About 52% of the biomass (2.33 g m^{-2}) produced would not survive to become smolts, but this biomass lost to natural mortality would become available to other trophic levels (*sensu* production forgone).

The freshwater production from the area required to produce one adult is 3,494 g of juvenile salmon annually (4.76 g m^{-2} yr^{-1} times 734 m^2) (Table 3).

Table 2. Production of juvenile Atlantic Salmon and Yellow Perch during the defined time intervals (usually annual, exceptions defined in text). Most Yellow Perch data are for Lake Oneida, but production is also shown for littoral habitat for Bay of Quinte for comparison (Randall et al. 2012).

Atlantic Salmon

Interval	W_1	W_2	G	D_1	D_2	B_1	B_2	M	B	P	B_m
0–0	0.20	1.61	2.09	1.20	0.90	0.24	1.45	0.29	0.67	1.41	0.17
0–1	1.61	6.99	1.47	0.90	0.22	1.45	1.54	1.41	1.49	2.19	1.13
1–2	6.99	16.23	0.84	0.22	0.04	1.54	0.65	1.70	1.03	0.87	0.84
2–3	16.23	25.00	0.43	0.04	0.03	0.65	0.73	0.32	0.69	0.30	0.19
Total									3.88	4.76	2.33

Yellow Perch

Interval	W_1	W_2	G	D_1	D_2	B_1	B_2	M	B	P	B_m
0–1	3.16	18.54	1.77	0.186	0.017	0.56	0.32	2.33	0.42	0.75	0.38
1–3	18.54	135.45	1.99	0.017	0.003	0.32	0.41	1.72	0.36	0.72	0.30
Total									0.79	1.47	0.68
Littoral										1.37	

W_1,W_2 are weights before and after the time period; G is instantaneous growth rate; D_1, D_2 are densities before and after the time period; B_1,B_2 are biomass; M is instantaneous mortality; P is production, and B_m is biomass lost to natural mortality. Formulae for estimating G, B, B_m, M and P are given in the text. Littoral production from Randall et al. (2012).

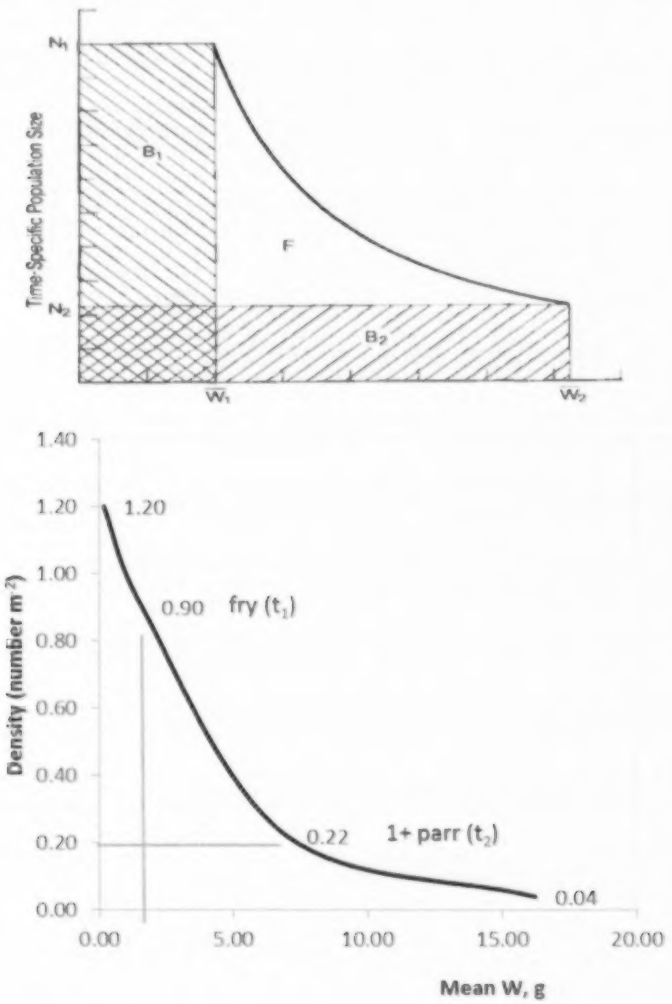

Figure 2. Upper: generalized Allen curve showing time-specific production by body-size. F is the biomass made available to other trophic levels (reproduced from Rago 1984). Lower: Allen curve for the production of Atlantic salmon from age 0 (t_1) to age 1 parr (t_2) (the numbers shown on the curve are number at t_1 and t_2).

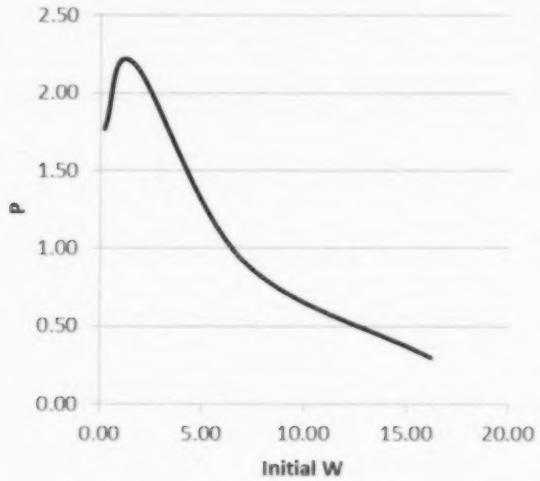

Figure 3. Relationship between body size (W, g) and production rate (g m^{-2} y^{-1}) of juvenile Atlantic salmon. The initial ascending portion of the relationship was for production for a short time period only (emergence to age 0 at mid-summer); otherwise the juvenile production estimates were annual.

Table 3. Comparison of area needed to produce one adult fish (APR) with total biomass production for that area as complementary metrics of productivity. Biomass lost to natural mortality is also shown (B_m).

Atlantic Salmon

Age	P (g m^{-2} y^{-1})	B (g m^{-2})	B_m	APR (m^2)	Total P (g y^{-1})	Total B (g)	Total B_m
0-0	1.41	0.67	0.17	734	1032	494	125
0-1	2.19	1.49	1.13	734	1607	1097	829
1-2	0.87	1.03	0.84	734	637	756	617
2-3	0.30	0.69	0.19	734	218	504	139
Total	4.76	3.88	2.33	734	3494	2850	1710

Yellow Perch

Age	P (g m^{-2} y^{-1})	B (g m^{-2})	B_m	APR (m^2)	Total P (g y^{-1})	Total B (g)	Total B_m
0-1	0.75	0.42	0.38	719	539	302	273
1-3	0.72	0.36	0.30	719	518	259	216
Total	1.47	0.79	0.68	719	1057	561	489

YELLOW PERCH

Juvenile Yellow Perch density (m^{-2}) ranged from 0.078 (age 0) to 0.0016 (age 3) (Table 1). Total biomass for these age groups averaged 0.55 g m^{-2}. Average survival to adult recruits (age 3) was 0.018, resulting in an estimate of area-per-recruit of 719 m^2.

Production rate decreased with age from 0.75 (age 0 to age 1) to 0.72 g m^{-2} y^{-1} (age 1 to age 3) (Table 2). Note the latter estimate was for production for two age groups. Also, production from emergence to fry was not included in this estimate, nor was production by Yellow Perch older than age 3. About 46% of the biomass produced (0.68 g m^{-2}) would not survive to the end of the time period, but would contribute energy to other trophic levels sometime during the period. These estimates of production and biomass lost are underestimates for the population because the production of larvae and production of the older age groups were not included.

The freshwater production from the area required to produce one adult was 1,057 g y^{-1} (Table 3). This estimate is for the whole lake, on average. Production in littoral habitat may be different (likely higher).

GENERIC PRODUCTION

The number of fish in each age class equivalent to one recruit at the age-of-maturity (Figure 4) decreases with age and as body size increases. Age-specific production forgone, however, was much greater (orders of magnitude) for species in larger size classes (Figure 5). Within a size class production forgone decreases with age. Similar patterns occur for production per area of habitat (Figure 6). Production forgone per m^2 is greater in rivers than lakes due to higher expected densities (Figure 6).

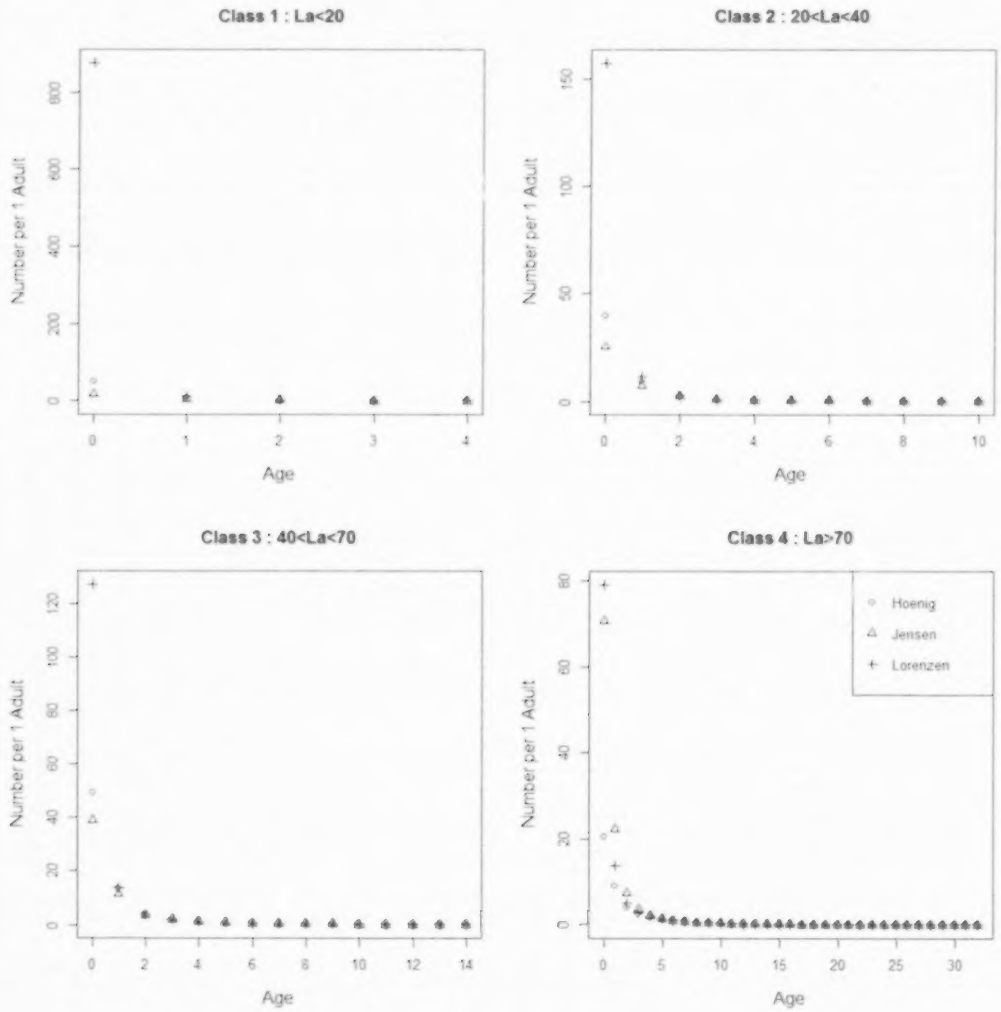

Figure 4. Estimated numbers of fish for each age class equivalent to one adult at the age-of-maturity for each size class using the three mortality estimators. This is equivalent to a loss of habitat equal to age class-specific APR.

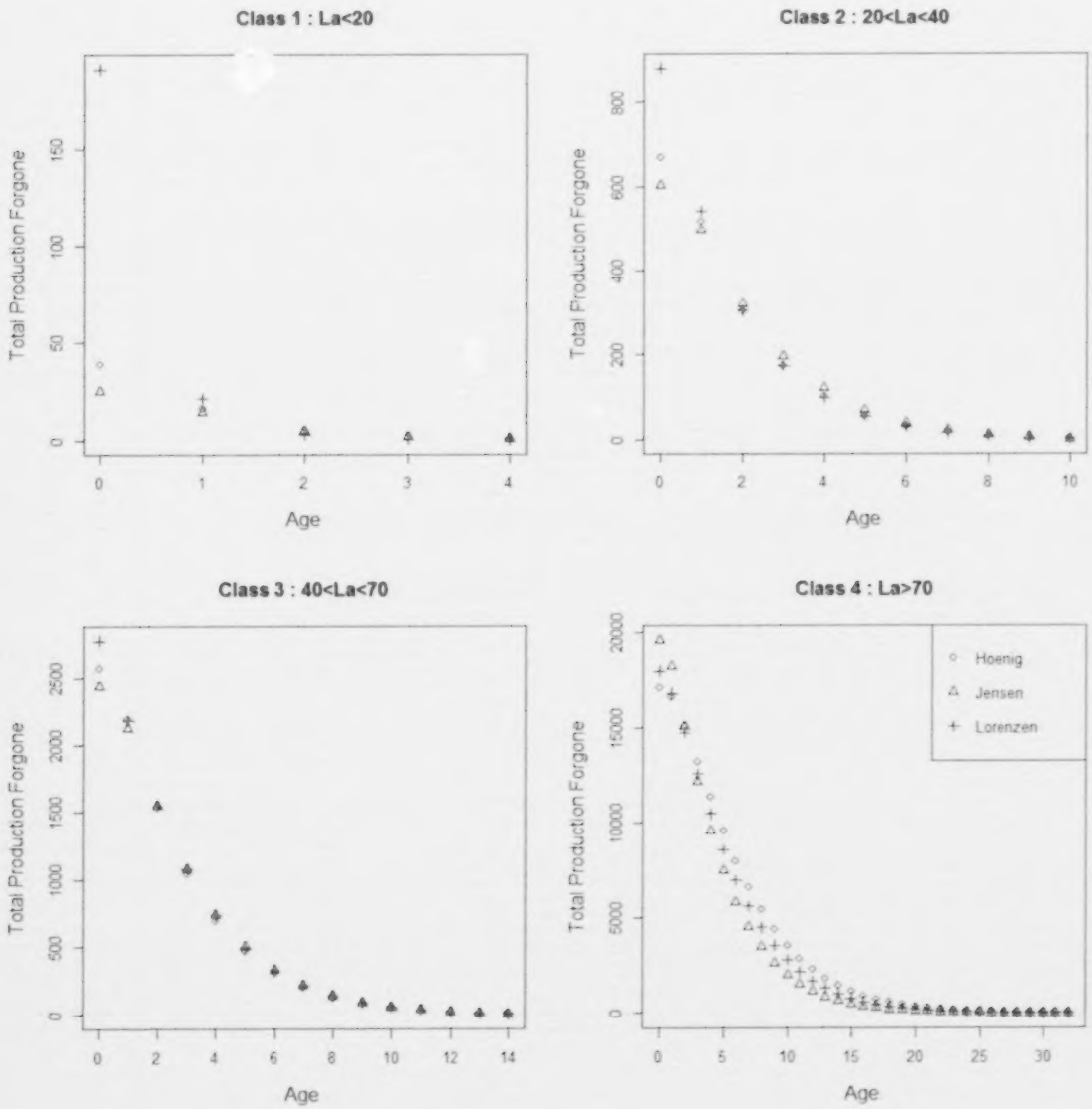

Figure 5. Total production forgone (g) for the loss of the number of individuals equal to one adult at the age-of-maturity (Figure 4).

The Lorenzen mortality allometry produced lower survival estimates than the other two mortality estimators resulting in greater estimates of fish per age class equivalent to one recruit (Figure 4) and lower production forgone estimates per unit of habitat lost for young age classes (Figure 6).

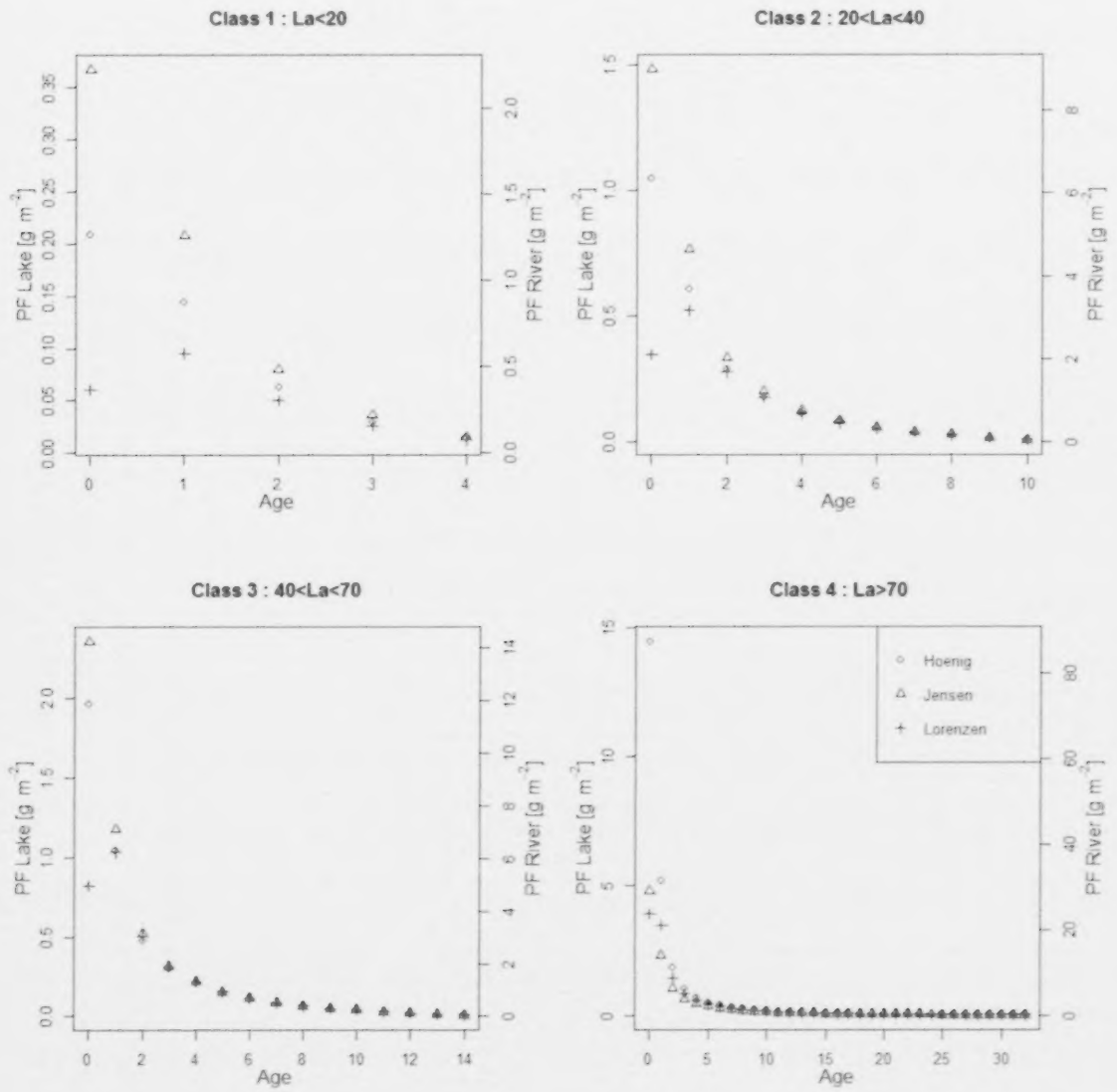

Figure 6. Production forgone per m^2 of habitat lost in a lake (left axis) and river (right axis).

DISCUSSION

Fish production rate is the implicit ecological foundation of equivalent adults or any other metric that is used to express the productivity of fish habitat. The calculation of production for age groups growing and surviving to become adults as was done for the two species in this study makes this biological foundation explicit. Area-per-recruit for each of the species provided a spatial context for estimating production forgone. An equivalent adult as a numerical currency has a corresponding prerequisite production per year for the area per recruit. Production is the best measure of ongoing productivity, and estimates of production forgone are consistent with the need to track project consequences to contributions to fisheries productivity as stated in the

amendments to the *Fisheries Act*. Before discussing the feasibility of fish production as a common metric for assessing impacts to habitat, the results and limitations of the case studies and generic production estimates are discussed.

Detailed field survey data of juvenile salmon densities and weight at age from the Southwest Miramichi River were required for estimating freshwater production. Because of their value for recreational and Aboriginal fisheries, empirical data on Atlantic Salmon in New Brunswick are extensive, involve many life-stages, and are long term. The strength of the juvenile salmon data were that they were quantitative (biomass g m^{-2}) and were collected using a consistent and standardized backpack electrofishing protocol. Because the surveys were long term, the salmon densities were monitored during different salmon management scenarios and varying adult and juvenile abundances. Commercial fishing was closed and mandatory catch and release of large salmon was initiated in 1984 (Douglas et al. 2013), allowing a large proportion of returning female salmon to survive to spawn in the rivers. As a consequence, fry and parr densities increased after 1984 (Figure 1), and the population approached or possibly reached carrying capacity. The ability to assess benchmarks of juvenile productivity was a major strength of using this dataset. A weakness for assessing feasibility of production forgone as a productivity metric was that the data were not summarized for different habitat types; the average densities represented a range of fluvial habitat conditions. All surveys were conducted in wadeable streams and rivers, but the depth, flow, substrate and proximity to spawning areas varied. Fluvial habitat suitable for all life stages, from emergent fry to pre-smolts, was surveyed using a fixed-site survey strategy. Hypothetically, if a portion of the fluvial habitat was lost to infill or if a nursery tributary was no longer accessible, the production potentially lost from that area could be estimated. Assessing change to habitat quality rather than quantity, affecting components of production, would however require habitat-specific data (e.g., riffles, runs and pools) on the affected habitat and changes to vital rates. Despite being data-rich, the spatial resolution of salmon densities in different habitats was not assessed for this study.

The use of existing data on densities and growth of juvenile Atlantic Salmon from the Southwest Miramichi was opportunistic, and was used as an example to demonstrate the estimation of production forgone if suitable data were available. Data from the SW Miramichi River were chosen in this case study, but it is important to emphasize that the productivity of salmon varies within the major tributaries of the Miramichi (Douglas et al. 2013) and even more so elsewhere in Atlantic Canada (Chaput et al. 2010; Power and Power 1994; Gibson 2006). Knowledge of regional or watershed-dependent benchmarks of productivity could inform the use of production as a productivity metric if the desire was to apply this approach more broadly.

The value of the long term and data rich database on Yellow Perch abundance was evident from Lake Oneida as well. A potential weakness, the use of gill-net data to monitor abundance, was offset by research in Lake Oneida on estimates of catch efficiency (Jackson et al. 2010), and on conversion to absolute units of abundance (number ha^{-1}). A weakness of the Oneida data was the lack of area-specific densities from littoral habitat, where projects affecting habitat were likely to occur. Limited data from littoral habitat in the Bay of Quinte (Lake Ontario) indicated that production was similar to the whole-lake Oneida estimates, but it is possible that the productivity of Yellow Perch, particularly juveniles, may be higher in littoral than pelagic areas. The Bay of Quinte data were based on an assumed catch efficiency, which was uncertain (Randall et al. 2012) and it may have been an underestimate. If densities of Yellow Perch were shown to be higher in littoral than pelagic areas of lakes, different habitat weighting factors could be used for these habitat types to estimate adult equivalence and APR.

If no population specific data are available, production could be estimated using the generic size classes, literature based survival values, and estimates of APR. However, the precision associated with APR estimates was low (see error bars in DFO 2015, Figure 3). The generic

approach is expected to be useful for describing general ecological patterns, but may not be sufficiently accurate to produce exact predictions of values (Pepin and Miller 1993).

Production forgone was estimated assuming permanent reductions in habitat quantity (e.g., loss of wetted area such as infill). Production forgone of impacts to habitat quantity that are finite (e.g., a duration of 3 or 5 years) could also be estimated for each of the affected year-classes, as was done by Rago (1984). Even if the loss of habitat quantity was finite, it may be judged to be permanent depending on the duration of the impact with respect to the life history of the species.

In summary, it was feasible to use fish production as a metric for assessing impacts (and offset requirements) to habitat area, if detailed data are available for the population in that geographic region. For assessing impacts to habitat quality, fish densities and body size would be needed for specific habitat types. If habitat-specific biomass was known, and if a project affects certain age-groups more than others, body size (and associated production) could be used as a weighting factor to judge the significance of impacts.

Production is advantageous in that the productivity metric is expressed in energy units (biomass) and the biomass of fishes lost to natural mortality is included in the productivity metric. Productivity is region-specific, as is explicit in the Atlantic Salmon literature. Regional benchmarks of productivity would be needed to broadly apply fish production as a metric in the different regions across Canada. If population specific data are not available, the generic body size classes used in this study would provide a reasonable starting point for assessment, but with low precision. The two approaches, equivalent adults and production forgone, are complementary.

Based on this preliminary analysis, further work on evaluating feasibility of production forgone as a metric for habitat management, both population-specific and generic, is warranted.

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